Tunnel junctions in narrow-gap $Hg_{1-x}Cd_xTe$ barrier structures in a magnetic field

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Direct interband tunneling, tunneling with the participation of deep levels, and thermally activated tunneling in longitudinal and transverse magnetic fields in $Hg_{1-x}Cd_xTe$ Schottky barriers (and *p-n* junctions) with $x \simeq 0.2$ and $x = 0.29$ were investigated in the temperature range $4.2\ K < T < 250\ K$. For both orientations the effects are significantly stronger than in the previously studied *p-n* junctions based on semiconductors with wider gaps. The experimental results obtained in parallel fields electric and magnetic fields $E \parallel H$ are described well within the WKB approximation taking into account the nonparabolicity of the bands. In crossed fields $E \perp H$, the anomalies expected in the electric and magnetic field dependences of the tunneling current near the critical fields $H_{cr} = cE/s$, corresponding to a transition from the state of unquantized infinite motion to finite motion (s is the Kane velocity), were not observed—tunneling also occurs in fields $H > H_{cr}$. The crossed-field results can be explained only by taking into account nonresonant subbarrier multiple scattering. The scattering length determined from the ratio of the magnitudes of the effects obtained with the two field orientations is proportional to $(H)^{-1/2}$ and it is close to the magnetic length for all H, E, and T, as expected for quantum diffusion in a magnetic field.

1. INTRODUCTION

In semiconductors with a Kane dispersion law the character of the carrier motion in external fields is substantially different, depending on the ratio of the magnitudes and the relative orientation of the electric (E) and magnetic (H) fields.[1–3] In parallel fields $E \parallel H$ the spectrum is always quantized and interband tunneling is possible in arbitrarily strong magnetic fields. In crossed fields $E \perp H$ quantization occurs only for $H/E > c/s$ (s is the Kane velocity), and motion in the direction of the field E in this limit is finite and there is no interband tunneling. Interband transitions in crossed fields $E \perp H$ are possible only in magnetic fields $H < H_{cr} = cE/s$, corresponding to the unquantized spectrum. Tunneling in parallel and crossed fields has been investigated experimentally in tunnel junctions based on PbTe (Ref. 4) and GaSb, GaAs, and Ge (Refs. 5 and 6), but because of the high values of the electric field $E \sim 10^6$–10^7 V/cm, and therefore also of H_{cr}, which are necessary to observe tunneling in such relatively wide-gap materials, the investigations were limited to magnetic fields below H_{cr}. The physically most interesting range of magnetic fields near and above H_{cr} with $H \perp E$ has also not been investigated in the well-studied InSb *p-n* junctions,[7–10] though tunneling in these junctions is already significant in fields $E \sim 10^5$ V/cm and the critical magnetic fields are relatively low $H_{cr} \sim 50$–100 kOe.

The most appropriate object for investigating the characteristic features of tunneling near critical fields, corresponding to a transition from infinite to finite motion, are structures based on narrow-gap semiconductors of the type $Hg_{1-x}Cd_xTe$, in which, thanks to the smallness of the gap width ε_g and the effective mass m_l, tunneling currents predominate in electric fields $E \sim 10^4$ V/cm, which corresponds to H_{cr} of the order of several kOe. The most favorable situation for investigations of this type occurs in Schottky barriers (SBs). In such structures the conditions of a uniform electric field, employed in theoretical calculations, are easily realized experimentally, with reverse biases, while in tunnel diodes the potential is substantially nonlinear, and often no reliable information about the real distribution of the potential is available. The possibility of varying the band gap in $Hg_{1-x}Cd_xTe$ by changing the composition and temperature makes it possible to investigate the dependence of tunneling in a magnetic field on the band parameters of the material. Since the effects associated with paramagnetic splitting of the spectrum make different contributions, it is of interest to make a comparative investigation of *p-n* junctions and SBs.

2. EXPERIMENTAL RESULTS

We investigated current transport in *p-n* junctions and Schottky barriers based on *p*-$Hg_{1-x}Cd_xTe$ with $x \simeq 0.2$ and $x = 0.29$ in magnetic fields up to 50 kOe, oriented perpendicular and parallel to the interface, in the temperature range $T = 4.2$–250 K. The method of preparation of the structures investigated and the predominant mechanisms of current transport were described previously in Ref. 11. The composition x and the doping levels $N_A - N_D$ of the starting material, the barrier height φ_0 (ε_g for a *p-n* junction), the basic parameters of the reverse branches of the I-V characteristic (the voltage V_L, corresponding to a transition from direct interband tunneling to tunneling through deep levels (DLs), and the temperature T_{min} of the transition from pure tunneling to activated tunneling), the range of electric fields E in the accessible interval of reverse biases and the corresponding critical fields $H_{cr} = Ec/s$ are presented in Table I.

The electric-field dependence of the reverse tunneling current with $H = 0$ and $H = 45$ kOe are presented in Figs. 1 and 2. For both orientations of the magnetic field a strong decrease of the tunneling current (up to a factor of 10 and more, which is much stronger than the effect in previously studied material) is observed both for biases $V < V_L$ corresponding to direct interband tunneling (transitions from the light-hole band into the conduction band in *p-n* junctions

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TABLE I. Basic parameters of the starting material and the reverse branches of the I-V characteristic ($T = 80$ K).

Sample No.	x, Rel. un.	$N_A - N_D$, cm^{-3}	φ_0, ε_g, meV	$-V_L$, V			T_{min}, K	$E\cdot 10^{-4}$, V/cm	H_{cr}, kOe
				$H = 0$	$H = 45$ kOe				
					$H \parallel E$	$H \perp E$			
1	0,21	$1\cdot 10^{16}$	100	0,35	0,45	0,48	95	2 — 4	20 — 40
2	0,22	$4\cdot 10^{15}$	80	0,15	0,23	0,25	110	0,8 — 2,5	8 — 25
3	0,29	$6\cdot 10^{15}$	160	0,45	0,48	0,64	120	2,4 — 3,5	24 — 35

Note: Pb-p-$Hg_{1-x}Cd_xTe$ p-n junction (1) and Schottky barrier (2, 3).

and at the Fermi level of the metal in SBs), and for tunneling with the participation of DLs ($V > V_L$). The effect is two and more times weaker for $V > V_L$ than for $V < V_L$, and this results in a displacement of the characteristic inflection point on the I-V characteristic $V_L = V_L(H)$ in magnetic fields for high reverse biases. Similar changes in V_L also occur with increasing T because the interband tunneling current I_t and the current associated with tunneling through DLs I_{tL} have different temperature dependences.[11] Consequently, the range of biases accessible for investigation of the magnetic-field dependences of I_t where the tunneling mechanisms are the same for all $H < H_m = 50$ kOe and T are restricted to relatively high negative values $V < V_L(H_m, T)$, especially for samples with $x = 0.29$. In p-n junctions and SBs with $x \simeq 0.2$ at temperatures $T < 50$ K the interband tunneling current predominates for all V for both $H = 0$ and $H = H_m$ [Fig. 1 (curve $2a$) and Fig. 2] and the $I_t(H)$ dependences can be investigated experimentally all the way to very weak reverse biases.

The magnetic-field dependences of the tunneling current $I_t(H)$ in SBs and in a p-n junction with $V < V_L$ are presented in Figs. 3 and 4. According to Figs. 1–4, the effect of a magnetic field for $Hg_{1-x}Cd_xTe$ structures with different compositions is significantly different. For samples with $x \simeq 0.2$ effects in both orientations are comparable in magnitude. In SBs with $x = 0.29$ the effect in crossed fields is several times stronger than in parallel fields both in the region of interband tunneling and for $V > V_L$.

In Ref. 11 we showed that anomalous temperature dependences of the tunneling I-V characteristics are a characteristic feature of $Hg_{1-x}Cd_xTe$ SBs: The tunneling currents decrease strongly with increasing temperature and they increase only at temperatures $T > T_{min}$ (see Table I), corresponding to a transition into the activated-tunneling regime. For sample No. 2 the I-V characteristics in Fig. 1 are presented for two temperatures $T = 30$ K and $T = 70$ K, while in Figs. 3 and 6 the magnetic field dependences for $E \perp H$ and

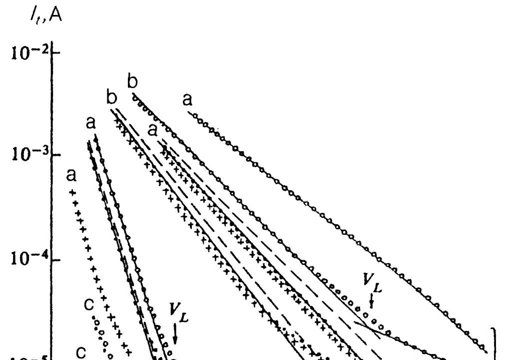

FIG. 1. Electric-field dependences of the tunneling component of the current in a Schottky barrier in magnetic fields $H = 0$ and $H = 45$ kOe for different temperatures $T = 30$ K (a), 70 K (b), and 170 K (c): the numbers on the curves are the sample numbers; dots—experimental data (O—$H = 0$; ●—$H \parallel E$; +—$H \perp E$); solid lines—calculation according to Eq. (1a) for $H = 0$ and Eq. (3) for $H \parallel E$; dashed lines—calculation according to Eq. (1) for $H \perp E$.

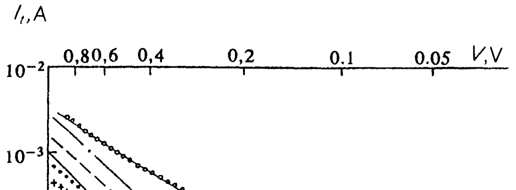

FIG. 2. Electric-field dependences of the tunneling current in a p-n junction with $H = 0$ and $H = 45$ kOe at $T = 30$ K: dots—experimental data (O—$H = 0$; ●—$H \parallel E$; +—$H \perp E$); solid lines—calculation according to Eq. (1a) for $H = 0$ and Eq. (3) for $H \parallel E$, dashed lines—calculation according to Eq. (5), dot-dashed lines—calculation according to Eq. (4) for $H \parallel E$.

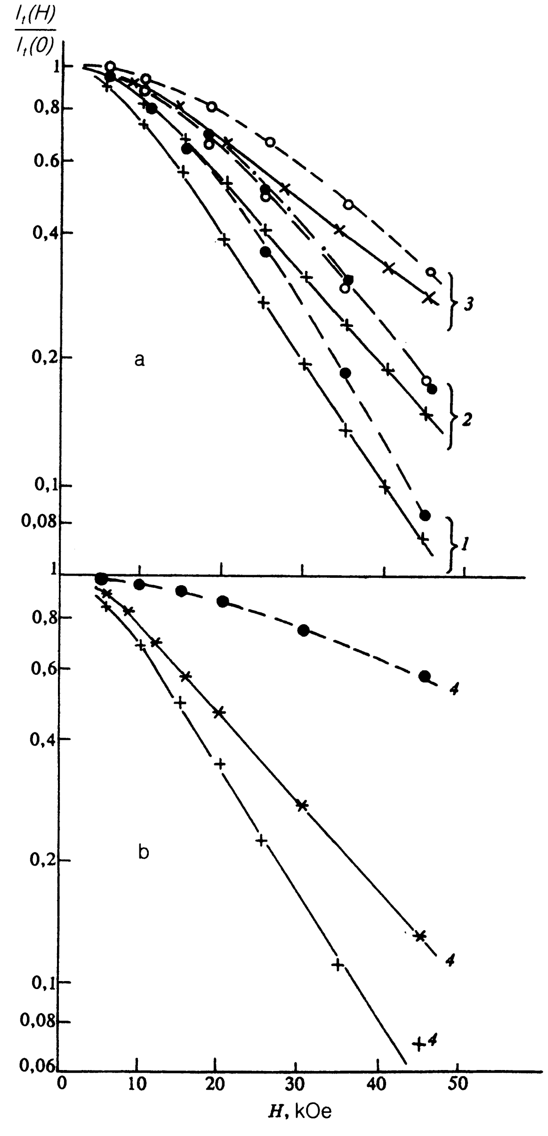

FIG. 3. Magnetic-field dependences of the tunneling current in Schottky barriers for samples 2(a) and 3(b) with $-V = 15$ V (*1*), 0.3 (*2*), 0.5 V (*3*), and 0.65 V (*4*) and $T = 30$ K (●, +), 70 K (0, ×), and 170 K (*): dots and solid lines—experimental data (●, ○—$H \parallel E$; +, ×, *—$H \perp E$), dashed lines—calculation according to Eq. (1), dot-dashed lines—calculation according to Eq. (3) for $H \parallel E$.

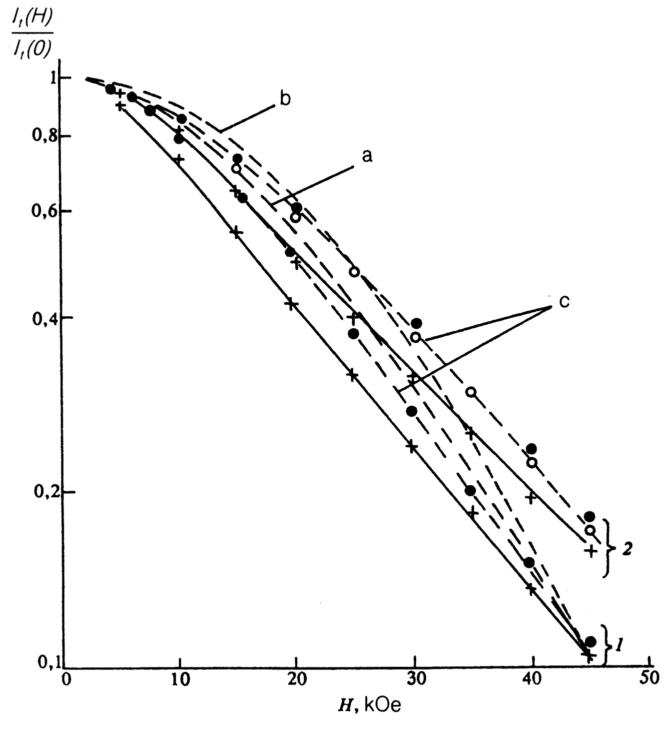

FIG. 4. Magnetic-field dependences of the interband tunneling current in a *p-n* junction with $-V = 0.15$ V (*1*), 0.4 V (*2*) and $T = 30$ K (●, +), 80 K(○): dots and solid lines—experimental (○, ●—$H \parallel E$; +—$H \perp E$), dashed lines—calculation according to the formulas (3) (a), (4) (b), and (5) (c).

$E \| H$ are presented for the same temperatures. Although at temperatures from 20 K to T_{min} the tunneling decreases by an order of magnitude and more, the field dependences $I_t(H)$ and $I_{tL}(H)$ at all temperatures in this range are equal within the range of the experimental error.

The curves *3c* for the wide-gap sample No. 3 in Fig. 1 at $T = 120$ K refer to the temperature range $T > T_{min}$, where the *I-V* characteristics are determined in the entire range of reverse biases by the activated-tunneling current I_T (the characteristics are straight lines in the coordinates ln I versus V). One can see (see also curve 4 for 170 K in Fig. 3) that the character of the magnetic-field dependences and the ratio of the effects for two orientations of the magnetic field are close to those for field emission. However, the magnitude of the effect $L_T(H)/I_T(0)$ is smaller for the activated tunneling current and is virtually independent of the voltage, while for $T < T_{min}$ the ratio $I_t(H)/I_t(0)$ decreases significantly with increasing $-V$ (Fig. 1, curves *2a* and *2b*). This is also equally valid for SBs with $x \simeq 0.2$.

3. DISCUSSION

A. Schottky barriers in parallel fields

Magnetic-field effect in *p-n* junctions have been investigated theoretically in detail.[1–3,9,12–14] In the case of SBs, however, as far as we know, such calculations and experimental studies have not been performed. The calculations can be performed quite simply in the WKB approximation by analogy to *p-n* junctions, where the quasiclassical approach describes adequately effects occurring in magnetic fields.[2,12,14] In the two-band Kane approximation for the dispersion laws and with a linear potential in the space charge region (SCR) of the semiconductor the interband tunneling current, normalized to its value at $H = 0$

$$I_t(0) = I_{t0}\exp(-k_\beta \lambda^0) \tag{1a}$$

(the expression for the pre-exponential factor is given in Ref. 11) in parallel fields $H \| E$ is described, within the quasiclassical approximation for the tunneling probability in the SB,[15] by the expression

$$\frac{I_t(H)}{I_t(0)} = 2B\gamma \sum_{n,\sigma}^{\infty} \frac{1 - \exp\{-A(Q_n^2 - \beta^2)^{1/2}\}}{1 - \exp\{-A(1 - \beta^2)^{1/2}\}} \left(\frac{1 - \beta^2}{Q_n^2 - \beta^2}\right)^{1/2} \times \exp\{-k_\beta \lambda^0 (k_Q Q_n^2 - 1)\}, \tag{1}$$

where

$$A = 4\lambda^0(-eV - \eta)/\pi\varepsilon_g,$$

$$Q_n^2 = \varepsilon_n^2/\varepsilon_g^2 = 1 + 4[(n + 1/2)\hbar\omega_c + \sigma g^* \mu_B H/2]/\varepsilon_g,$$

$$\lambda^0 = \pi m_l^{1/2} \varepsilon_g^{3/2} / 2^{3/2} e\hbar E = \pi m_l^2 s^3 / e\hbar E,$$

$$\omega_c = eH/m_l c, \quad \mu_B = e\hbar/2m_0 c,$$

$$\sigma = \pm 1, \quad \gamma = sH/cE,$$

e is the electron charge; m_0 and m_l are, respectively, the mass of a free electron and the mass of a light hole; $g^* = g_{n,m} - g_l$, where g_l, g_n, and g_m are the g factors of a light hole, electron in the semiconductor, and electron in the metal, respectively. The coefficients $B = \arcsin \alpha^{1/2}$, $k_\beta = f(\beta)$, and $k_Q = f(\beta/Q_n)/f(\beta)$ are associated with the nonparabolicity of the bands; and,

$$f(x) = 1/2 + [x(1 - x^2)^{1/2} + \arcsin x]/\pi;$$

$$\beta = 2\alpha - 1; \quad \alpha = \varphi_0/\varepsilon_g.$$

For sufficiently large reverse biases $(-eV - \eta) > \varphi_0$ in the space charge region important for tunneling the electric field in the SB is close to its maximum value at the boundary with the metal:

$$E = 2[2\pi(N_A - N_D)(\varphi_0 - eV - \eta)/\varkappa]^{1/2}, \tag{2}$$

where $\varkappa$ is the permittivity of the semiconductor and η is the Fermi energy in the semiconductor, measured from the top of the valence band.

In the derivation of Eq. (1) it was assumed that the position of the Fermi level with respect to the top of the heavy-hole band at the interface is independent of the magnetic field. In contrast to the corresponding expressions for *p-n* junctions,[2,12–14] the formula (1) was derived without assuming that the cyclotron energy is small ($\hbar\omega_c \ll \varepsilon_g$), which is often violated in narrow-gap $Hg_{1-x}Cd_xTe$ structures. For $a > 0.3$–0.4 [in the investigated SBs based on *p*-type materials $\varphi_0 \sim 2\varepsilon_g/3$ (Ref. 11)] k_Q is virtually independent of a and in the region $\hbar\omega_c \ll \varepsilon_g$ the expression (1) can be put into the form

$$\frac{I_t(H)}{I_t(0)} = Z\frac{\mathrm{ch}(Zg^* m_l/2m_0)}{\mathrm{sh}\, Z}, \tag{3}$$

where $Z = 2k_\beta \lambda^0 \hbar\omega_c/\varepsilon_g = k_\beta \pi\gamma$. In the limit $\varphi_0 \to \varepsilon_g$, so that $k_\beta = 1$ and $Z = \pi\gamma$, the expression (3) is identical to the expression for the interband tunneling current in *p-n* junctions.[13] For tunneling in *p-n* junctions based on Kane semiconductors[0,1] $g^* = 0$ (transitions with spin flap) and paramagnetic splitting (neglecting spin-orbit effects) does not affect the tunneling current in a magnetic field. In SBs, $g^* \simeq g_l \simeq m_0/m_l$, since $g_l \gg g_m$, and the strength of the effect under otherwise the equal conditions is expected to be $\sim\cosh(Z/2)$ times weaker than in *p-n* junctions.

For *p-n* junctions the expression (3) actually does not contain the material parameters and the strength of the effect in parallel currents is determined only by the parameter $\gamma = sH/cE$, i.e., the ratio of the electric and magnetic fields ($s \simeq 10^8$ cm/s and is approximately the same for all Kane semiconductors). If α does not depend strongly on the composition, i.e., the barrier height $\varphi_0 \propto \varepsilon_g$, as happens for the structures investigated, then the conclusion that for $H \| E$ the effect is independent of the parameters of the material is also valid for SBs. This result depends on the fact that as $\varepsilon_g \propto m_l$ decreases the increase in $\hbar\omega_c$ and, therefore, the increase $\Delta\varphi_0 \propto \hbar\omega_c \propto m_l^{-1}$ of the additional effective potential in a magnetic field is completely compensated for by the decrease of the tunneling length $a \simeq \varepsilon_g/eE$ and the "tunneling" effective mass [of course, the tunneling current itself increases exponentially with decreaseing ε_g (Eq. (1a)]. In strong fields ($\hbar\omega_c \sim \varepsilon_g$) such a compensation SBs in practice occurs in and breaks down somewhat in *p-n* junctions [$I_t(H)/I_t(0)$ increases by only 20–40% when ε_g increases by a factor of 2–3]. It follows directly from what was said above that $I_t(H)/I_t(0)$ is also independent of the temperature. Although the temperature-induced changes in the barrier height $\Delta\varphi_0(T)$ [$\Delta\varepsilon_g(T)$ in *p-n* junctions] for narrow-gap materials are comparable in order to magnitude to φ_0 and ε_g,[11,16] the temperature dependence of $I_t(H)/I_t(0)$, according to Eq. (3), is determined only by the temperature dependence $E(T)$. For sufficiently large negative biases, $(-eV-\eta)>\varphi_0, \varepsilon_g$, where interband tunneling predominates mainly, the electric field at a given bias is virtually independent of T, so that $I_t(H)/I_t(0)$ is also independent of temperature, in complete agreement with experiment. For SBs this result was obtained under the assumption $\alpha=\varphi_0/\varepsilon_g=$ const, and the fact that experimentally $I_t(H)/I_t(0)$ is independent of T indicates that the assumption emloyed above that the Fermi energy at the interface is independent of H is acceptable.

The electric-field dependences of the tunneling current calculated on the basis of Eqs. (1) and (3) are presented in Fig. 1 together with the experimental dependences [for the region $V>V_L$ the I-V characteristics with $H=0$ were calculated according to the formula (3) from Ref. 11]. For $H=0$ the experimental voltage dependences $I_t(V)$ agree with the theory for all temperatures T. This indicates that for the structures investigated the approximation of a uniform electric field is acceptable and the relation (2) for the voltage dependence $E(V)$ is valid. As far as the I-V characteristics in a magnetic field are concerned, the experimental I-V curves $I_t(V)$ in a field $H=45$ kOe are described well for all samples and all temperatures by the approximate relation (3), while the more accurate formula (1) overestimates $I_t(H)$, but it correctly describes the character of the dependence I_t on the electric field (see Fig. 1). The discrepancy between Eqs. (1) and (3) is greatest for the sample with $x\simeq0.2$, in which the condition $\hbar\omega_c\ll\varepsilon_g$ in the field $H=45$ kOe is not as well satisfied because of the smallness of ε_g and the cyclotron mass.

Since in parallel fields the tunneling current in structures based on Kane semiconductors is determined only by the ratio E/H, magnetic-field effects actually provide a direct method for measuring the electric field in such structures with linear variation of the potential. The values of E determined from the magnitude of the effect in the field $H=45$ kOe are plotted in Fig. 5 as a function of the reverse bias together with the theoretical dependences (2). In accordance with what we have said above, the relation (1) leads to values of E that are somewhat lower than the values obtained with Eq. (3), but the discrepancies do not exceed 10–15%. The relations (1) and (3) give practically the same values of E when the values of $I_t(H)/I_t(0)$, measured in weak magnetic fields $H\sim10$ kOe, where the effect is weak, are used.

The calculated relations (1) and (3) for $I_t(H)$ are compared in Fig. 3 to the experimental relations. The value of the electric field employed in the calculations was determined from the condition that the theoretical curves match the experimental curves in a magnetic field $H=45$ kOe [and according to Fig. 1 it is different for the approximations (1) and (3)]. For all biases for which direct interband tunneling predominates, the theory of Eq. (1) is in good agreement with the experiment for all magnetic fields investigated. The field dependences $I_t(H)$ are also described well within the approximation (3), although for the narrow-gap sample No. 2 deviations from the theory, which, generally speaking, fall outside the limits of the measurement errors, are observed for fields in the range $H=15$–30 kOe.

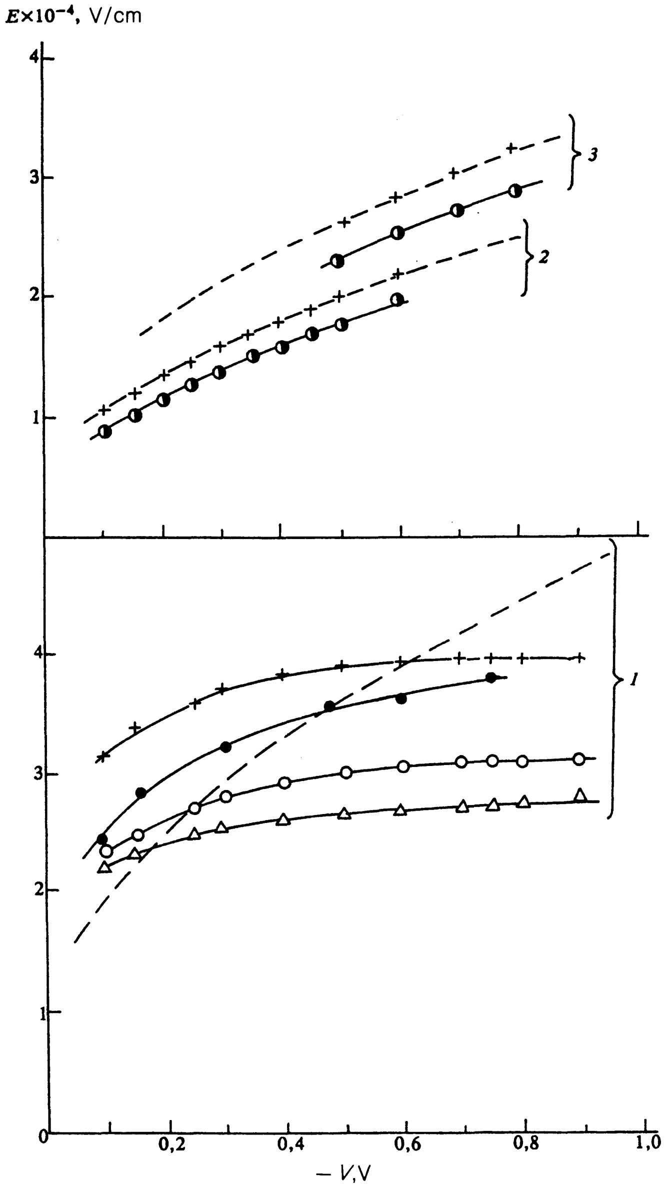

FIG. 5. Electric field versus the reverse bias: the numbers on the curves are the sample numbers; dots and solid lines—experimental values of E and values calculated according to the formulas (1a)—●; (1)—◑; (3)—+; (4)—△; (5)—○; dashed lines—Eq. (2).

B. *p-n* junctions in parallel fields

The theory developed in a number of works[9,12,13] for interband tunneling in *p-n* junctions in parallel fields $H\parallel E$ leads to the expression (3) with $\beta=1$ and $g^*=0$, irrespective of the approach employed. A somewhat different expression for $I_t(H)$ was obtained in Ref. 2 ($g^*=0$):

$$I_t(H)/I_t(0)=2\pi\gamma\sum_{n=0}^{\infty}Q_n^4\exp\{-\lambda^0(Q_n^2-1)\}. \tag{4}$$

In the indicated calculations, however, the approximation $\hbar\omega_c\ll\varepsilon_g$ was used, while in the *p-n* junctions studied in fields $H\sim50$ kOe the cyclotron energy was $\hbar\omega_c\sim(0.8$–$1)\varepsilon_g$. A calculation using an approach similar to the employed above for calculating the current in an SB (1) leads to the expression

$$I_t(H)/I_t(0) = 2\pi\gamma\sum_{n=0}^{\infty}\exp\{-\lambda^0(k_Q Q_n^2 - 1)\}, \qquad (5)$$

which is valid for all H and differs from Eqs. (3) and (4) by the factor $k_Q = f(1/Q_n)$ at Q_n, which reduces the magnitude of the effect in strong fields $\hbar\omega_c \sim \varepsilon_g$, in the argument of the exponential function. The use of the uniform-electric-field approximation in the derivation of Eqs. (3)–(5) is also typical for calculations of the tunneling current in p-n junctions with $H = 0$.[17] Owing to the exponential dependence of I_t on E, regions with the maximum field E_{max} should make the largest contribution to the tunneling current. Indeed, the fact that the agreement between experiment and calculations of $I_t(0)$ when E_{max} is used is better than that obtained with the mean-field theory is, as was recently pointed out in Ref. 18, quite general for p-n tunnel junctions. In the implanted $Hg_{1-x}Cd_xTe$ diodes studied here the p side is weakly doped and the p-n junction is sharply asymmetric (assuming that the p material is uniformly doped near the metallurgical boundary of the p-n junction). The potential distribution in this case is close to the distribution in the SB, and for sufficiently large reverse biases the electric field E is constant in a significantly larger part of the SCR than happens in traditional tunnel diodes in which both sides of the p-n junction are strongly doped. It is significant that the field is uniform precisely in the p region adjoining the p-n junction, where E is maximum, the dependence of E_{max} on V being determined by the same relation (2) with $\varphi_0 = \varepsilon_g$.

As one can see from Fig. 2, in contrast to SBs, the theoretical I-V characteristics of p-n junctions with $H = 0$ calculated using Eq. (2) and $E(V)$ disagree significantly with the experimental characteristics. The disagreement between the theoretical and experimental electric-field dependences of I_t in a magnetic field is even greater. For all approximations (1a) and (3)–(5) the theory predicts significantly stronger V dependence of both the tunneling current itself and the magnitude of the effect in a magnetic field. The values of $I_t(H)/I_t(0)$ computed with the reverse bias increasing from $V = -0.15$ to $V = -0.8$ V decrease by more than an order of magnitude (from 10 to 25 times depending on the approximation employed), while experimentally the magnitude of the effect in this range of V changes by only a factor of two. Since the bias dependence of $I_t(H)/I_t(0)$ is completely determined by the dependence $E(V)$, the observed discrepancies indicate that the effective electric field changes less as the voltage on the structure changes than is implied by the relation (2). This result also agrees completely with the character of the deviation of the experimental I-V characteristics from the characteristics computed with $H = 0$—the increase in the tunneling current and therefore the electric field with increasing reverse bias are appreciably less than theory predicts.

Clearly the discrepancy cannot be associated with the fact that in the calculations E is replaced by its maximum value, since taking into account the nonlinearity of the potential is equivalent to decreasing the effective electric field in the tunneling exponential, and should lead to an even larger discrepancy with experiment. The most likely reason why the relation (2) does not describe adequately the voltage dependence $E(V)$ is that the distribution of the electrically active defects in the weakly doped p region of diode structures is nonuniform, which is not unexpected for implanted p-n junctions. Owing to the decrease in the degree of compensation, the excess density of acceptors in the p region can increase substantially away from the physical interface.[16] The decrease in the tunneling length with increasing reverse bias will be smaller in this case than for uniform doping, and this corresponds precisely to weakening of the voltage dependence of the effective electric field.

Any systematic calculations are difficult to perform within such a model not only because of the complexity of the problem, but also because there is no reliable information about the impurity distribution in implanted p-n junctions. The effective (for tunneling) electric field can be estimated experimentally from the differential slope of the I-V characteristic at $H = 0$. The voltage dependences $E(V)$ determined in this manner are displayed in Fig. 5. Figure 5 also displays the voltage dependences $E(V)$ determined from the magnitude of the effect in a parallel magnetic field of $H = 45$ kOe. Both methods give a significantly weaker bias dependence of E than is predicted by Eq. (2) with $N_A - N_D$ equal to its value in the initial $Hg_{1-x}Cd_xTe$. Different approximations of $I_t(H)$ give appreciably different values of E (by 20–50%), but if estimates based on Eq. (5) do not depend on H, then the relations (3) and (4) lead, in different magnetic fields H, to significantly different values of E, i.e., the electric field is not determined uniquely. This is illustrated well in Fig. 4 which displays the magnetic-field dependences of the tunneling current. Just as in Fig. 3, the computed curves $I_t(H)$ are made to match the experimental curves in a field $H = 45$ kOe by fitting the value of E. The expression (5) leads to field dependences $I_t(H)$ which agree very well with experiment, while the approximation (3), which agrees quite well with measurements in the case of materials with wider gaps (where, however, the recorded effects are much weaker), leads to deviations which are clearly larger than the measurement errors.

C. Schottky barriers and *p-n* junctions in crossed fields

Starting from the analogy to the two-band Kane approximation of the relativistic Dirac equation (to within the substitution $c \Rightarrow s$), the motion in crossed fields with $E > sH/c$ ($H > cE/s$) can be reduced to motion in only an electric (magnetic) field by transforming to a coordinate system moving with velocity equal to the drift velocity $v = Hs^2/cE$ ($v = cE/H$).[1] The expression for the interband tunneling current in the approximation of a uniform electric field E is obtained in this approach, as shown in Ref. 1, by simply replacing the electric field in the expression for I_t at $H = 0$ by its value in the new coordinate system $E \to E' = E(1-\gamma^2)^{1/2}$. In the case of p-n junctions it has the form[1]

$$\frac{I_t(H)}{I_t(0)} = (1-\gamma^2)\exp\left\{\lambda^0\left(1 - \frac{1}{(1-\gamma^2)^{1/2}}\right)\right\} \qquad (6)$$

(a similar expression but without the preexponential factor was also derived in Ref. 2). On the basis of this procedure the tunneling current in crossed fields $H \perp E$ can be calculated in an elementary fashion, and for SBs

$$\frac{I_t(H)}{I_t(0)} = (1-\gamma^2)\,\mathrm{ch}\,\frac{k_\beta \pi\gamma}{2}\exp\left\{k_\beta\lambda^0\left(1 - \frac{1}{(1-\gamma^2)^{1/2}}\right)\right\}. \qquad (7)$$

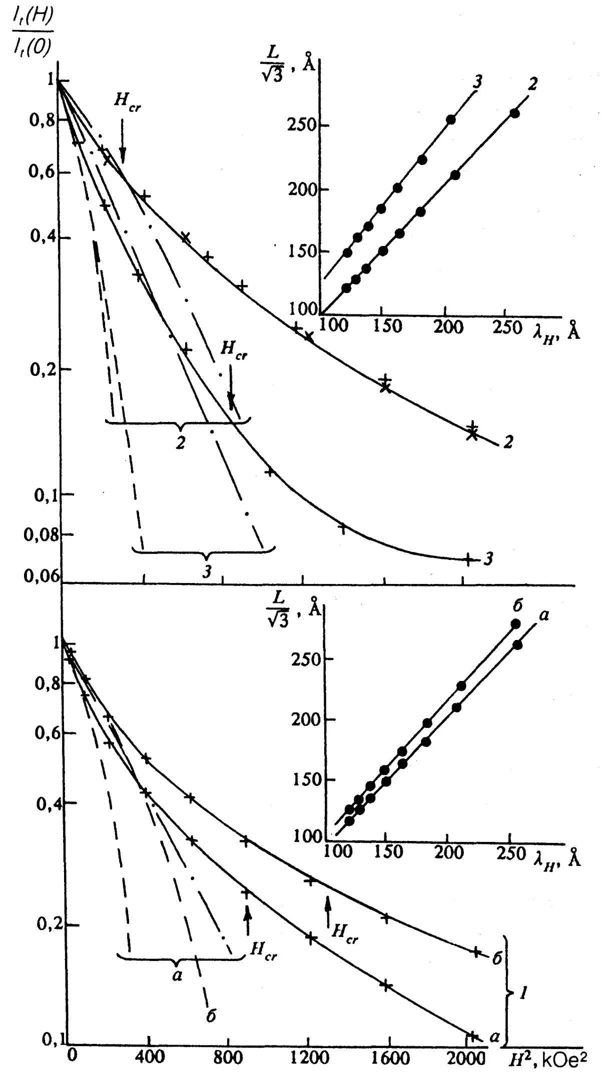

FIG. 6. Interband tunneling current versus H^2 for crossed fields $H\perp E$ and $-V=0.15$ V (a), 0.6 V (b), 0.3 V (2), and 0.65 V(3) and $T=30$ K(+) and 70 K (×): the numbers on the curves are the sample numbers; dots and solid lines—experimental data; dashed lines—calculation according to Eq. (6) for a *p-n* junction and Eq. (7) for a Schottky barrier; dot-dashed lines—calculation according to Eq. (8) for a *p-n* junction and Eq. (7) for a Schottky barrier in the approximation $\gamma \ll 1$. The dependences $L(\lambda_H)$ presented in the insets are identical for all temperatures $T < T_{\min}$ and biases $V < V_L$.

The expression (7) is analogous to the expression (6) to within the obvious substitution $\lambda^0 \Rightarrow k_\beta \lambda^0$ and the additional factor $\cosh(\pi k_\beta \gamma/2)$ due to the paramagnetic splitting, which is absent in view of the fact that $g^* = 0$ from the expression (6) for *p-n* junctions. For $H \ll H_{\rm cr}$ ($\gamma \ll 1$) the magnitude of the effect in *p-n* junctions, according to Eq. (6), is quadratic in the magnetic field

$$\ln I_t(H)/I_t(0) = -\lambda^0\gamma^2/2 = -\lambda^0 s^2 H^2/2c^2E^2, \qquad (8)$$

which agrees with the result of a simple quasiclassical calculation[12] for materials with a parabolic band.

The magnetic-field dependences (6)–(8) are compared with the experimental dependences in Fig. 6, where the arrows indicate the critical magnetic fields, corresponding to $\gamma = 1$, when according to Eqs. (6) and (7) the tunneling current vanishes. The critical fields $H_{\rm cr}$ were calculated using the values of E determined from the magnitude of the effect in parallel fields $H \parallel E$ (see Fig. 5). With the exception of the region of weak magnetic fields, which corresponds to a 10–15% decrease in the current, the experimental magnetic-field dependences for this orientation in both *p-n* junctions and SBs differ sharply from the theoretical dependences. The discrepancies in the magnitude of the effect reach several factors even in the region $H \sim H_{\rm cr}/2$, which at $H = H_{\rm cr}$, where the theory (6) and (7) predicts $I_t(H_{\rm cr}) = 0$, experimentally the tunneling current is not more than three times lower than its value at $H = 0$. No anomalies in the behavior of $I_t(H)$ are observed near $H_{\rm cr}$. The discrepancies between experiment and theory are just as large in the dependences of the magnitude of the effect of the reverse bias, the composition, and the temperature (in contrast to the case $H \perp E$, in the case $H \parallel E$ the values of $I_t(H) I_t(0)$ should depend, according to Eqs. (6)–(8), on λ^0, i.e., on m_l and ε_g and therefore also on the temperature).

The possibility that the tunneling transparency of the barrier in crossed fields is anomalously high compared with theory of Ref. 1 was considered in Refs. 19 and 20 (and pointed out in Ref. 1), where scattering in subbarier tunneling was taken into account. Scattering not only increases the probability of tunneling and removes the threshold of the effect with respect to the magnetic field, it also changes the character of the magnetic-field dependences $I_t(H)$. In the absence of information about the parameters of the scattering centers and their spatial distribution, we can confine ourselves to qualitative estimates of the magnitude of the effect. The additional magnetic potential $\Delta\varphi_\perp = m_1 \omega_c^2 x^2/2$ acquired in the direction of tunneling $x \parallel E$ in crossed fields drops to zero in the presence of scattering, and for scattering lengths L appreciably shorter than the tunneling length $a \simeq \varphi_0/eE$ the effect of the magnetic field reduces essentially to increasing the gap width and therefore the barrier height by

$$\overline{\Delta\varphi_\perp} \simeq (1/L)\int_0^L \Delta\varphi_\perp dx = m_l \omega_c^2 L^2/6. \qquad (9a)$$

On the basis of this analysis the effect of the magnetic field is analogous to the case $H \parallel E$, where the decrease in I_t is ultimately due to the increase (linear as a function of H) of the splitting between the Landau levels for the bands of the initial and final states:

$$\Delta\varphi_\parallel = \hbar\omega_c(1 - g^* m_l/2m_0)/2. \qquad (9b)$$

Since the hopping length in quantum diffusion in crossed fields is of the order of the magnetic length $\lambda_H = (c\hbar/eH)^{1/2}$ and therefore $\Delta\varphi_\perp \sim m_l \omega_c^2 \lambda_H^2/2 \propto H$, an analogy for two orientations should also exist in the magnetic-field dependences of I_t. The experimental curves $I_t(H)$, as one can see from Figs. 3 and 4, indeed become straight lines in the coordinates $\ln(I_t)$ versus H, while for structures with the composition $x \simeq 0.2$ in most of the field ranges studied the magnetic-field dependence $I_t(H)$ is actually the same for both orientations.

An expression for the current owing to tunneling diffusion in crossed fields can be obtained from the relation (1a) for $H = 0$ by making the substitution $\varphi_0 \Rightarrow \varphi_0 + \overline{\Delta\varphi_\perp}$, which in the case of not too strong fields, $H \ll 4am_l^2 s^2 c/e\hbar$, so that $\Delta\varphi_\perp \ll \varphi_0$, leads to

$$\frac{I_t(H)}{I_t(0)} \simeq \mathrm{ch}\,\frac{Z}{2}\exp\left\{-\frac{Z}{8\alpha}\left(\frac{L}{\lambda_H}\right)^2\right\}, \qquad (10)$$

where $Z = k_\beta \pi\gamma$. As before, the factor $\cosh(Z/2)$ is associated with paramagnetic splitting. The field dependence (10) differs from the relation (3) (in the similar approximation $\varphi_0 \Rightarrow \varphi_0 + \Delta\varphi_\parallel$ the argument in Eq. (3) $Z \Rightarrow Z' = 3k_\beta \pi\gamma/8\alpha$) only by the factor $(L^2/3\lambda_H^2)$ in the argument of the exponential, so that the characteristic scattering length L can be determined experimentally from the ratio of the tunneling currents in two orientations:[1)]

$$I_t(H_\parallel)/I_t(H_\perp) \simeq \exp\{3Z(L^2/3\lambda_H^2 - 1)/8\alpha\}. \qquad (11)$$

The values of L determined in this manner are plotted in the insets in Fig. 6 as a function of the magnetic length. For all structures and in the entire range of fields investigated L is proportional to λ_H, i.e., the ratio L/λ_H does not depend on the magnetic field, just as it does not depend on the bias (on E) or the temperature (and therefore, within certain limits, on the effective mass also), but it does depend somewhat on the composition. For p-n junctions and SBs based on materials with $x \simeq 0.2$ the scattering length $L \simeq 1.7\,\lambda_H$ and it is somewhat longer ($L \simeq 2\lambda_H$) in SBs with $x = 0.29$. Thus, since L/λ_H does not depend on E and H, the normalized tunneling current in crossed fields in the model under consideration depends, according to Eq. (10), just as in the case $H \parallel E$, only on the ratio H/E, while on the basis of the theory of Refs. 1 and 2, which neglects scattering, it is determined by H^2/E^3.

Subbarrier scattering is strongest when the size of the cyclotron orbit reaches, with increasing H, values less than the tunneling length $\alpha \simeq \varepsilon_0/eE$ ($\simeq \varepsilon_g/eE$ for a p-n junction); this is also in good agreement with experiment. Magnetic fields H_λ corresponding to the condition $\lambda_H \sim \alpha$ fall precisely into the region where the experimental dependences begin to deviate appreciably from the theory of Ref. 1. It is obvious that the most favorable conditions for manifestation of scattering in tunneling are realized in barrier structures based on narrow-gap semiconductors. Thanks to the smallness of ε_g (and therefore also φ_0 in SBs) and of m_l, in such structures tunneling currents predominate in weak electric fields for relatively long tunneling lengths a, so that the values $H_{cr} \sim E$ and, especially, $H_\lambda \sim \alpha^{-2}$ fall into the region of comparatively low H. For most previously investigated p-n junctions based on wider-gap materials either H_{cr} and H_λ fall outside the range of fields employed,[4–6,10] as estimates show, or the deviations from a theory which neglects subbarrier scattering are not discussed (the experimental data presented in Refs. 7 and 21 clearly indicate such deviations in fields $H \sim 100$ kOe).

In the two-band approximation employed above, the current associated with tunneling of heavy holes, for which quantization of the spectrum in a magnetic field starts in significantly stronger magnetic fields due to the high effective mass, was neglected. Analysis of tunneling on the basis of a more systematic multiband approach, which takes into account both the nonparabolicity of the light branches and the effect of the finite curvature of the heavy branch of the band Γ_8 (at least in the parameterized Luttinger form), encounters serious difficulties (in the case of SBs they are of a fundamental character due to the nonuniqueness of the boundary conditions imposed on the components of the spinors[22]). However, due to the smallness of the ratio of the effective masses of the light and heavy holes (in HgCdTe $m_l/m_h \sim 0.02$), the contribution of heavy holes to the total tunneling current can be estimated by the quantity

$$I_{th}/I_t \sim \exp\{-\lambda^0 k_\beta[16\alpha^{3/2}(m_h/m_l)^{1/2}/3\pi k_\beta - 1]\}$$
$$\sim 10^{-9} - 10^{-30},$$

which, even under the most unfavorable conditions (strong electric fields and low temperatures) cannot change appreciably the character of the magnetic field dependences and it especially cannot lead to "saturation" of the field dependences $I_t(H)$ in crossed fields at the level $I_t(H)/I_t(0) \sim 0.1$–0.001, as is observed experimentally. For the same reason (smallness of m_l/m_h) the mutual transformation of heavy and light holes in an electric field can also be neglected, especially since in crossed fields $H \perp E$ the probability of such transitions decreases rapidly with increasing H,[23] and this can only lead to a stronger field dependence $I_t(H)$ at $H \perp E$.

D. Magnetic field effects for other tunneling mechanisms

Together with the interband tunneling current, a magnetic field significantly influences both tunneling with participation of deep levels and thermally activated tunneling. The energy of the deep levels $\varepsilon_L - \varepsilon_V \simeq 0.45\,\varepsilon_g$ in the structures investigated is such that the condition of maximum tunneling transparency is satisfied $(\varepsilon_L - \varepsilon_V) \sim \varphi_0/2^{2/3}$ (Ref. 11) and the tunneling current through a deep level is described by an expression of the type (1a) with the exponent $\lambda^0\{1 - f[2(\varepsilon_L - \varepsilon_V)/\varepsilon_g - 1]/k_\beta\} = k_\beta \lambda^0/2$. We do not know of any theoretical works in which the influence of the magnetic field on both the resonance and activated tunneling current is studied. But these effects can be estimated on the basis of a simple quasiclassical analysis, similar to the method employed for analyzing interband tunneling. For the tunneling current through a deep level this results in the magnetic-field dependences (3) and (10) to within the substitution $k_\beta \pi\gamma \Rightarrow k_\beta \pi\gamma/2$. The character of the magnetic-field, electric-field, and temperature dependences of the tunneling current through a deep level is thus similar to that of direct interband tunneling, but the expected value of the quantity $\ln\,[I_{tL}(H)/I_{tL}(0)]$ is approximately two times smaller, as is observed experimentally. However, no special meaning should be attached to the quantitative agreement, since the estimates made are based on the assumption that the condition of maximum transparency holds in a magnetic field, which is not obvious a priori. Breakdown of this condition can result in changes in I_{tL} [in principle it also results in growth of I_{tL} in a magnetic field, if the relation $(\varepsilon_L - \varepsilon_V) \sim \varphi_0/2^{2/3}$ with $H = 0$ is not satisfied to a sufficient degree of accuracy] that are comparable in magnitude to the effect resulting from an increase in the height of the effective barrier in a magnetic field. As numerical estimates show, if the energy of the deep level with respect to the heavy-hole band does not depend on H or varies in a manner such that its position with respect to the light-hole and conduction bands remains the same, then the departure from resonance in the interval $H \leqslant 50$ kOe does not make a strong contribution to $I_{tL}(H)/I_{tL}(0)$. The approximate character of the calculations and the experimental errors in determining E_L and φ_0 preclude any unequivocal conclusion about possible changes in the energy of the deep level in a magnetic field.

Under the conditions of thermally activated tunneling ($T > T_{\min}$) the carriers tunneling from states lying above the Fermi energy by an amount $\varepsilon_m \gg kT$ make the main contribution to the current of the Schottky barrier. The optimal energy ε_m and therefore also the tunneling length $\alpha_T \simeq (\varphi_0 - \varepsilon_m)/eE$ depend on T and E, and this ultimately leads to temperature and electric-field dependences of the activated tunneling current that are different from tunneling at temperatures $T < T_{\min}$. Qualitatives estimates in this regime can be made quite simply in the parabolic dispersion law approximation. For linear variation of the potential the tunnel-activated current at $H = 0$ can be written, to a first approximation,[15] in the form

$$I_T(0) \simeq I_{T0}\exp\{-[\lambda_T(\varepsilon_m) + \varepsilon_m/kT]\}, \quad (12)$$

where

$$\lambda_T(\varepsilon_m) = 4(2m_l)^{1/2}(\varphi_0 - \varepsilon_m)^{3/2}/3e\hbar E,$$

$$\varepsilon_m \equiv \varepsilon_m(0) = \varphi_0 - (\hbar eE/kT)^2/8m_l.$$

The increment to the potential $\varphi_0 + \Delta\varphi(H)$ in a magnetic field $\hbar\omega_c \ll \varphi_0$ also gives rise to the increase $\varepsilon_m(H) = \varepsilon_m(0) + \Delta\varphi(H)$, where the increments $\Delta\varphi(H)$ are determined by Eqs. (9a) and (9b). In the parallel-field orientation $H \| E$ the substitution $\varphi_0 \Rightarrow \varphi_0 + \Delta\varphi_{\|}(H)$ results in the dependence

$$\ln I_T(H_{\|})/I_T(0) \sim \hbar\omega_c/2kT,$$

and more accurate calculations within the approximations employed in the derivation of Eq. (12) give the expression (3) with the argument $Z \rightarrow Z_T = \hbar\omega_c 2kT$. This substitution for the case of crossed fields $\varphi_0 \rightarrow \varphi_0 + \overline{\Delta\varphi_{\perp}}(H)$ leads to the dependence

$$I_T(H_{\perp})/I_T(0) \simeq (\text{ch } Z_T L^2/6\lambda_H^2)\exp\{-Z_T L^2/3\lambda_H^2\} \quad (13)$$

for thermally activated tunneling controlled by subbarrier scattering. Within the approximations employed the character of the magnetic-field dependences $I_T(H)/I_T(0)$ and the ratio of the magnitudes of the effects for two orientations in the activated tunneling regime are similar to the case of field emission, but the influence of the magnetic field decreases with increasing T and does not depend on the applied bias E, in complete agreement with the experimental results. As far as quantitative estimates are concerned, for Schottky barriers with $x = 0.29$ the experimental magnitudes of the effects in the field $H = 45$ kOe are somewhat larger than the computed values (by 10–20% for $H \| E$ and by a factor of ~ 1.5 for $H \perp E$ when using values of L determined in the region $T < T_{\min}$). Such discrepancies are entirely understandable, since the parabolic-band approximation for the Schottky barriers investigated is applicable only when the quite strong inequality $T \gg T_{\min}$ (when $\varphi_0 - \varepsilon_m \ll \varepsilon_g$) is satisfied, while reliable separation of the thermally activated current from the above-barrier injection background is experimentally possible only for small excesses, $T > T_{\min}$. Taking into account the nonparabolicity of the bands not only decreases the tunneling probability due to renormalization of the tunneling mass, but it also significantly shifts $T_{\min}$ in the direction of high temperatures.[11] In addition, the character of the temperature dependence $\varepsilon_m(T)$, determining the magnitude of effects in a magnetic field, also changes.

In conclusion we note that the unexpectedly strong effects occurring in the investigated structures in a magnetic field (including also in parallel fields $H \| E$) are also observed in the regime of above-barrier injection, but a discussion of these results falls outside the scope of this paper.

[1)]If scattering is negelected, $I_t(H_{\perp})/I_t H_{\|})$ is determined, according to Eqs. (3) and (8), by the electric field. This fact was employed in preceding works to determine E in *p-n* junctions based on wide-gap semiconductors, where Eq. (8) describes well the magnetic-field-dependence $I_t(H)$ in the investigated ranges of H (corresponding to changes in I_t in such diodes).

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